Accelerator Developments for eRHIC

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for eRHIC group

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IRs
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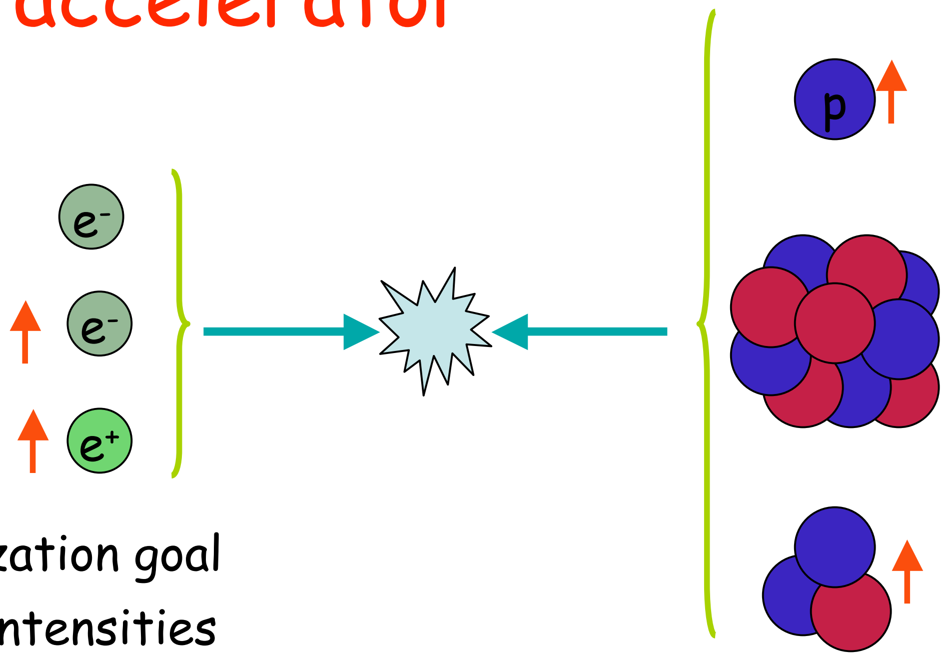
Content

- What is current vision of eRHIC
- Continued from last year - no surprises!
  - Development of R&D ERL and its components
  - Small gap magnets
  - Understanding and suppression of kink instability
  - Simulation of electron beam disruption in the collision
  - Simulations of the beam-beam effects on hadron beam
- New developments
  - Up-dated lattice for linac and loops
  - Effect of wake-fields
  - Effect of the coherent electron cooling on eRHIC design
  - Staging of eRHIC
  - Compact spreaders and combiners
  - IP with crossing angle
- Conclusions

eRHIC Scope -QCD Factory

Electron accelerator

RHIC



Unpolarized and polarized leptons 2-20 (30) GeV

Polarized protons
$_{25}\downarrow$ 50-250 (325) GeV

Heavy ions (Au)
50-100 (130) GeV/u

Polarized light ions
(He^3) 215 GeV/u

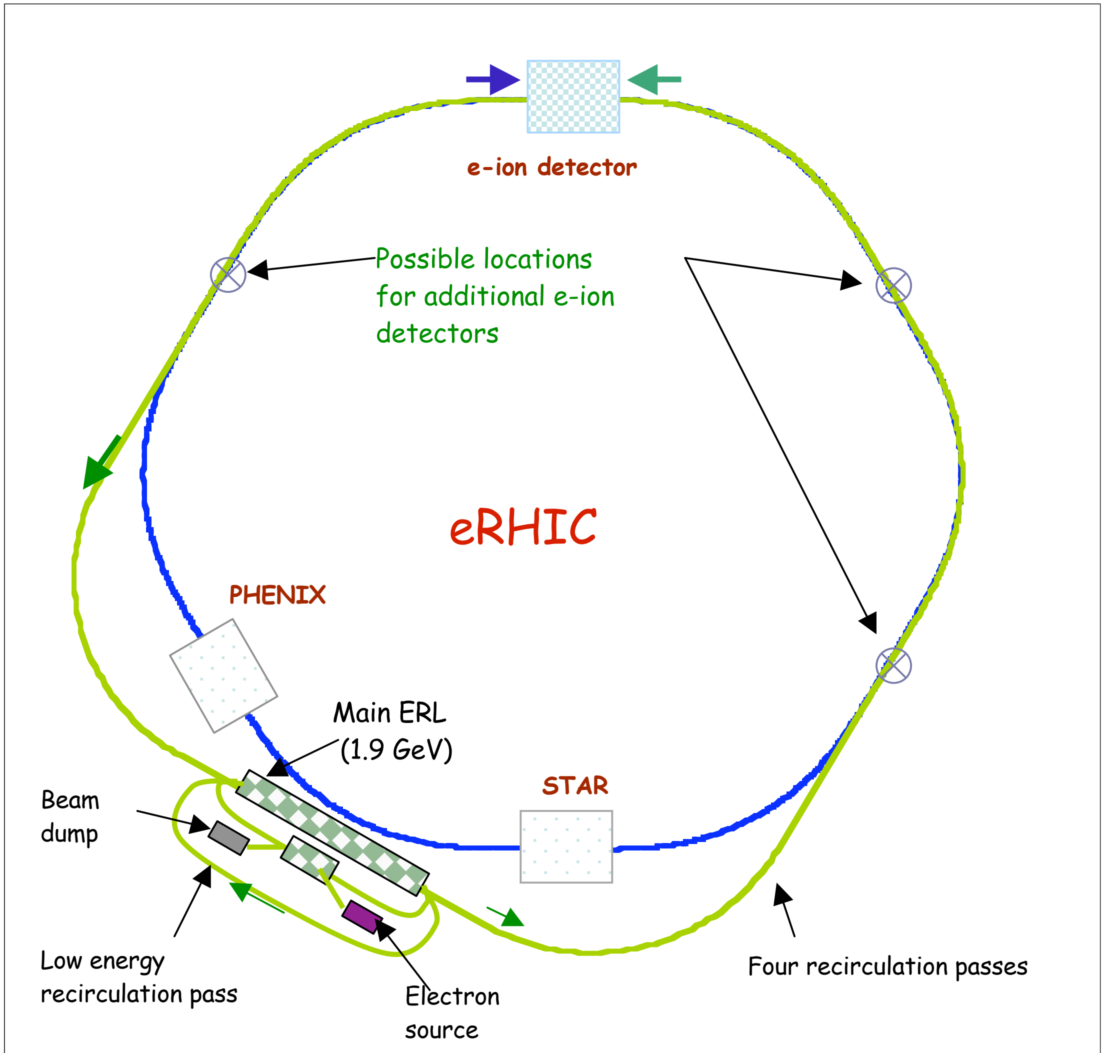
70% beam polarization goal

Positrons at low intensities

Center mass energy range: 15-200 GeV

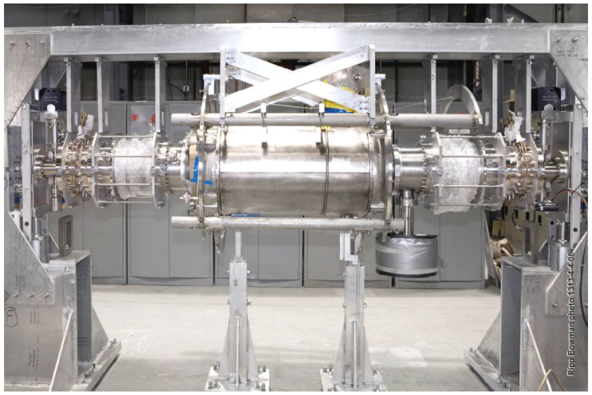
New requirements: eA program for eRHIC needs as high as possible energies of electron beams even with a trade-off for the luminosity. 20 GeV is absolutely essential and 30 GeV is <u>strongly desirable</u>.

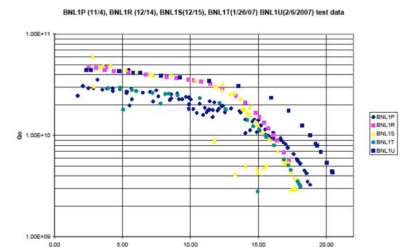
Baseline: ERL-based eRHIC

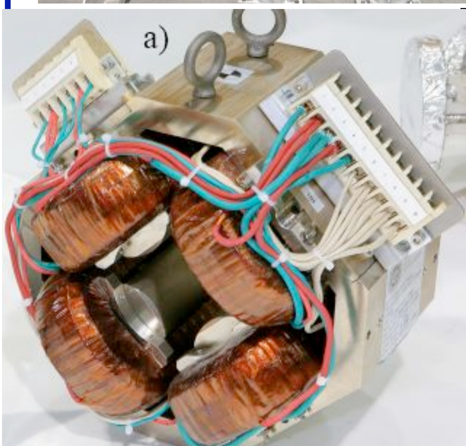


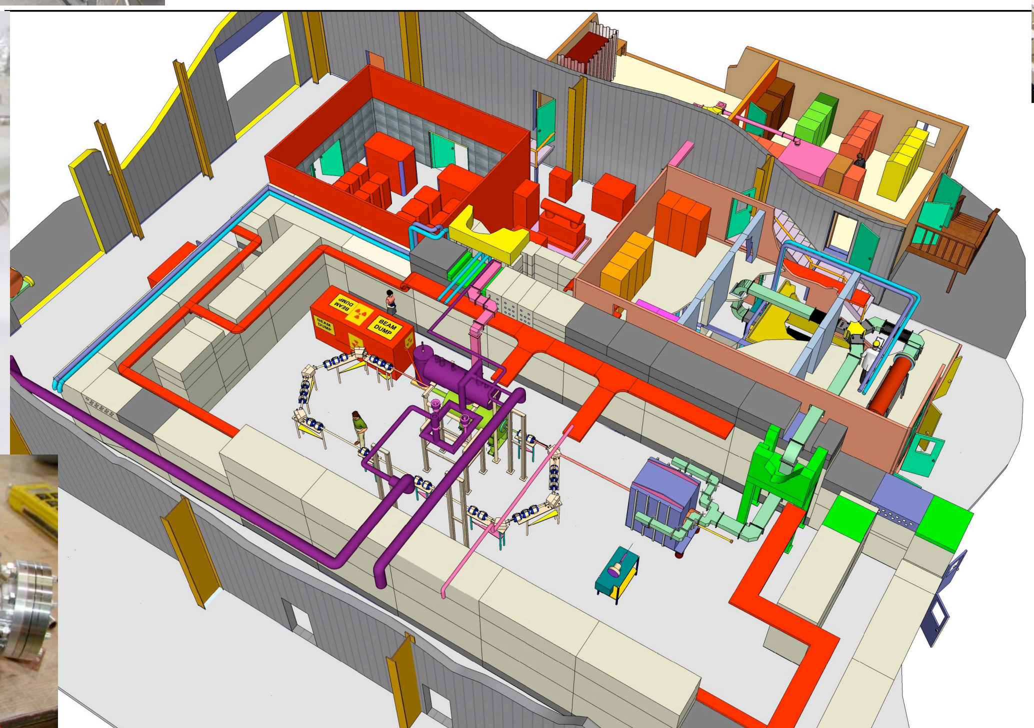
- 10 GeV electron beam energy, upgradeable to 20 GeV by doubling the main linac
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors
- Full polarization transparency at all energies for the electron beam
- Ability to take full advantage of transverse cooling of the hadron beams
- Possible options to include polarized positrons (compact storage ring; Compton backscattered) - Though at lower luminosity

R&D ERL Commissioning start 2009



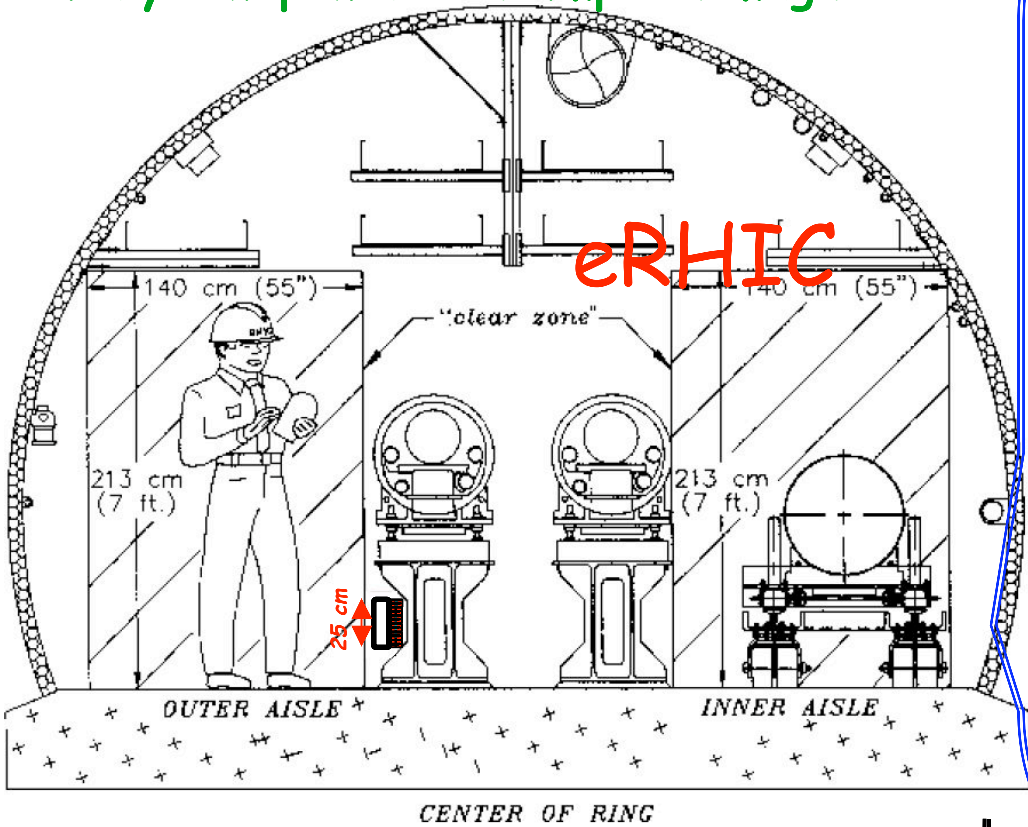


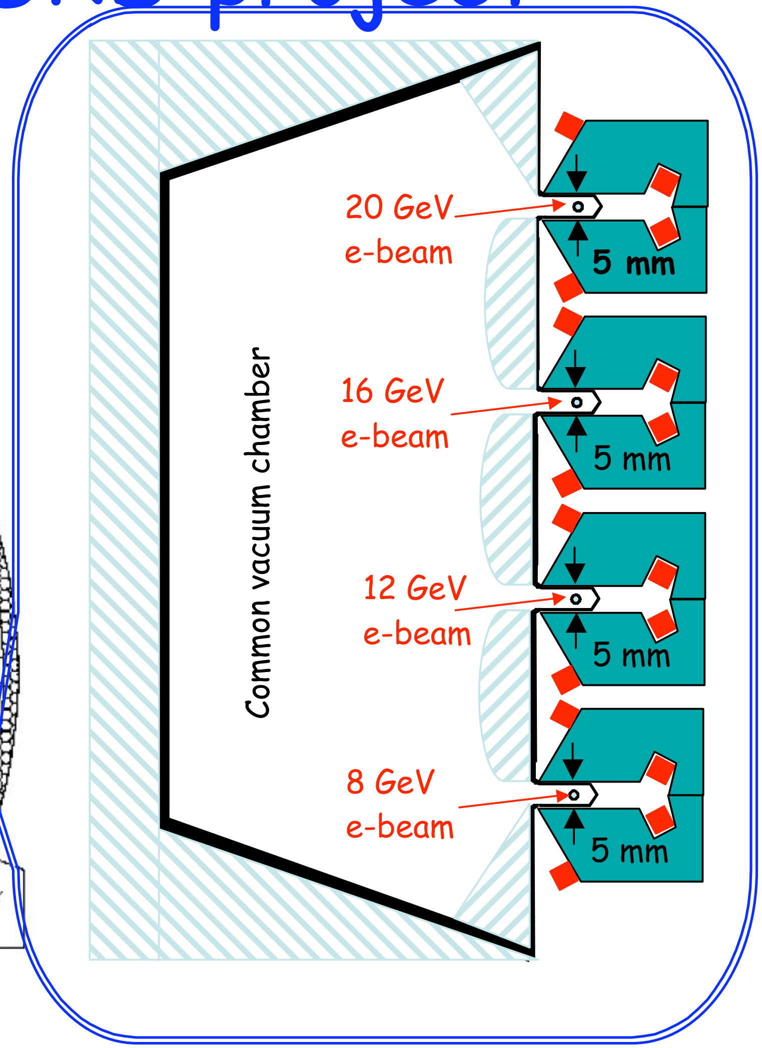


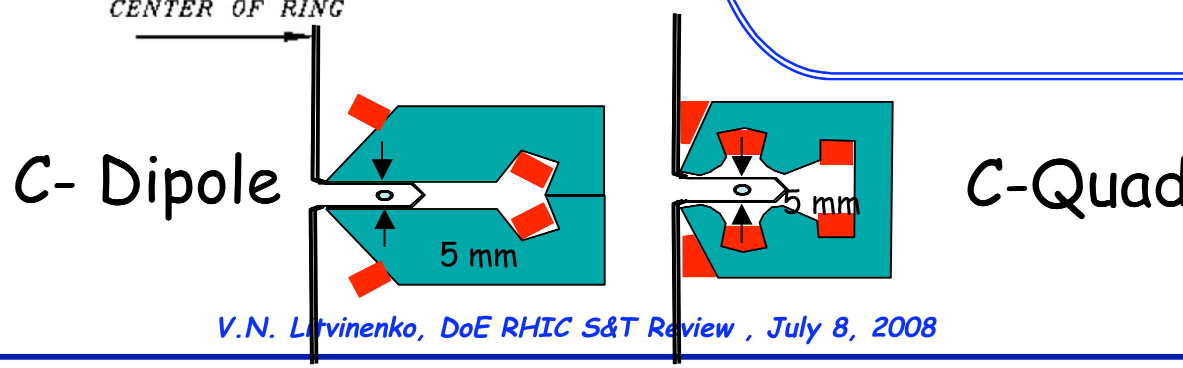


eRHIC loop magnets: LDRD project

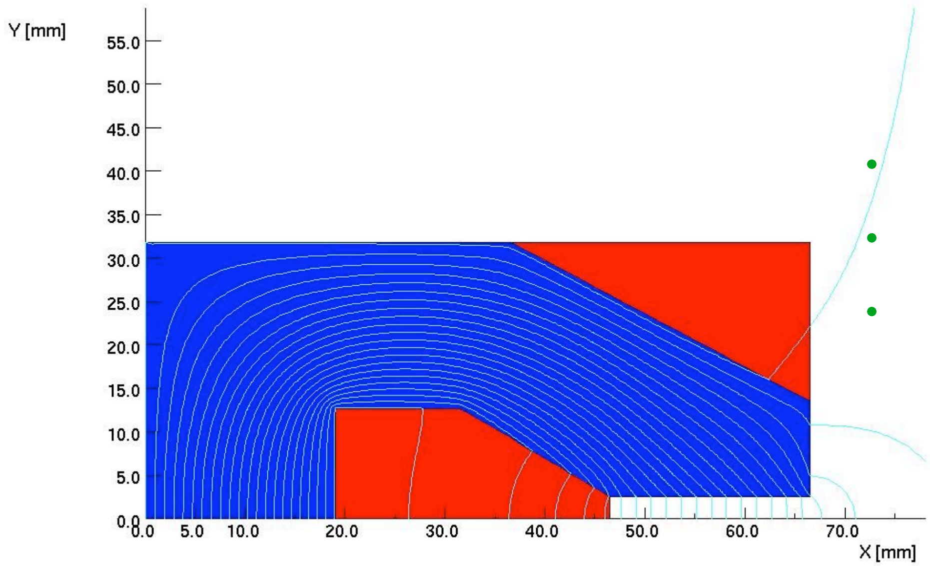
- Small gap provides for low current
- Very low power consumption magnets





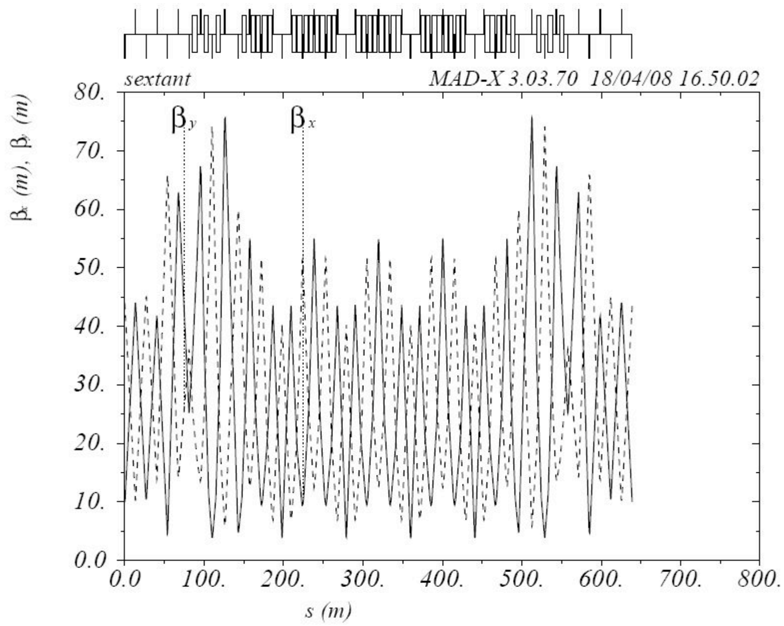


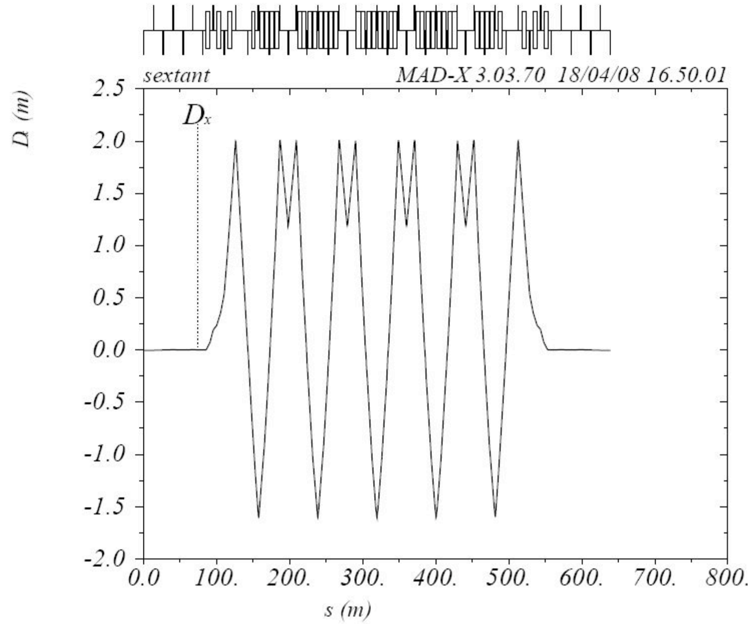
Design & studies of dipole magnet are underway



- Magnetic design - W.Meng
- Mechanical engineering - G.Mahler
- Post-doc Y.Hao is starting studies of the acceptable field errors and of the alignment tolerances

Recirculation Pass Optics Modification



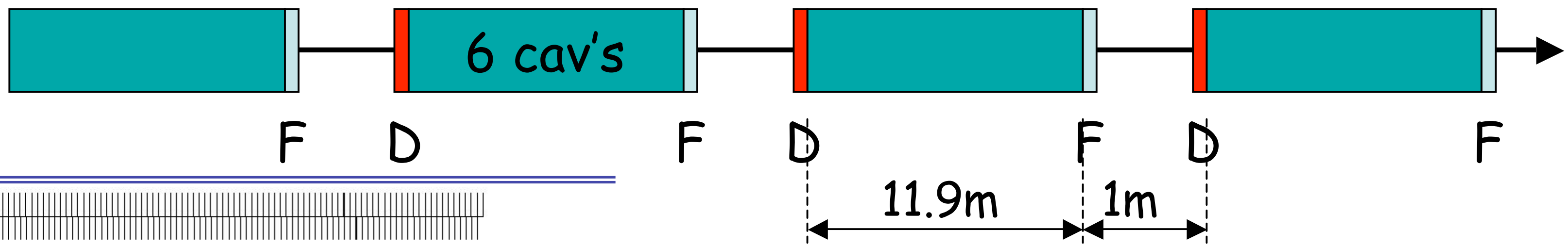


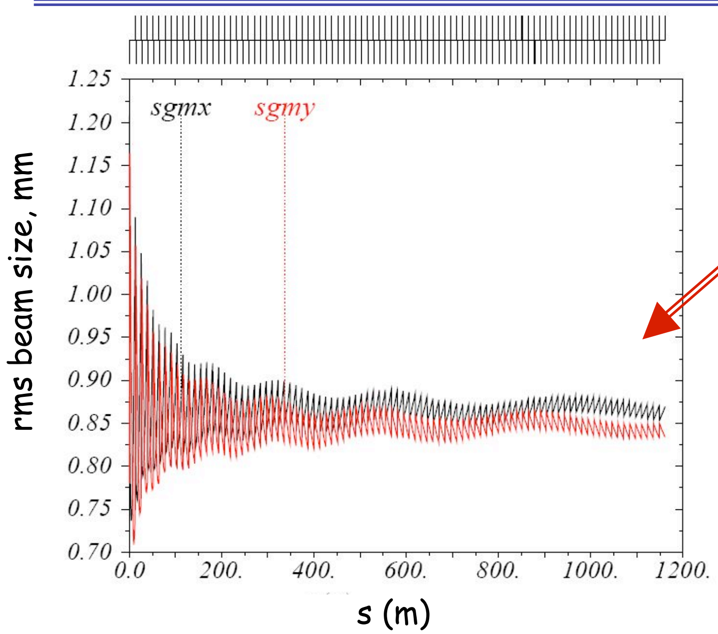
Other features:
-phase trombone (in the straight sections)
-path length control (at 12 o'clock region)
-initial design for separator/merger

The optics based on Flexible Momentum Compaction cell provides achromatic and isochronal transfer through each arc and allows for flexible adjustment of R_{56} parameter.

Compact linac design

Increased number of 700MHz cavities inside one cryostat to 6 cavities.
3rd harmonic cavities (2 per cryostat) for the momentum spread minimization.
Cavity gradient: 19.5 Mev/m; Average acceleration rate: 8.2 MeV/m;
Total length of 1.9 GeV linac: 232m (instead of ~360m in the previous design).





Evolution of rms beam sizes along the linac on all acceleration passes. Recirc.passes are presented by Unit matrix.
Doublet focusing (90° phase advance per cell)
Constant quadrupole gradient.

Compact linac design makes more realistic a design option with linac(s) placed inside the RHIC tunnel

Limitations on the aperture for electron beam

- Magnetic field quality
- Alignment accuracy
- e-beam loss
- resistive-wall induced energy spread and energy loss

Power loss and magnet aperture
(based on β=50m)

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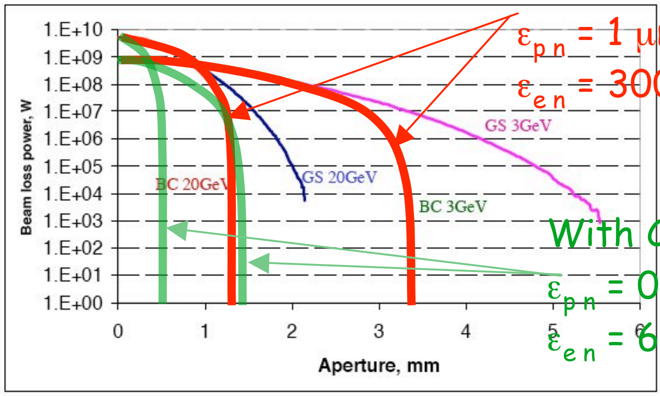
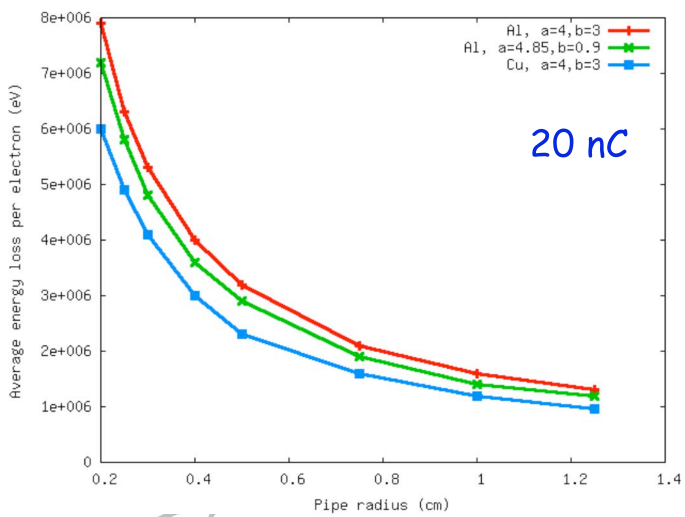


GS – Gaussian BC – Beer-Can



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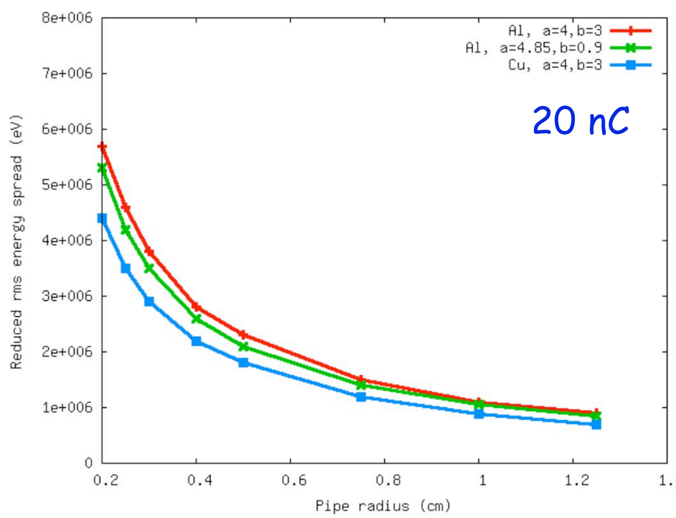
N_e = 20 nC/bunch/e

Loss ~1MW with 5 mm aperture

With CeC -

N_e -> 2 nC/bunch/e

Loss ~10kW with 5 mm aperture



Main advantages of ERL + cooling

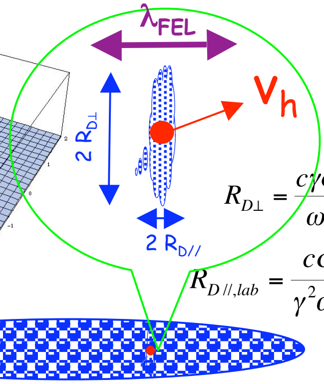
$$L = \gamma_p \frac{f_{col} N_p}{\beta_p^* r_p} \xi_p \qquad \xi_p = \frac{r_p}{4\pi} \cdot \frac{N_e}{\varepsilon_{p\ norm}};$$

$$\frac{N_e}{\varepsilon_{p\ norm}} = const \Rightarrow \xi_p = const; \quad L = const$$

$$N_e \propto \varepsilon_{p\ norm} \Rightarrow I_e \propto \varepsilon_{p\ norm} \Rightarrow P_{SR} \propto \varepsilon_{p\ norm}!$$

- Main point is very simple: if one cools the emittance of a hadron beam in electron-hadron collider, the intensity of the electron beam can be reduced proportionally without any loss in luminosity or increase in the beam-beam parameter for hadrons
- Hadron beam size is reduced in the IR triplets - hence it opens possibility of further β* squeeze and increase in luminosity
- Electron beam current goes down -> relaxed gun!, losses for synchrotron radiation going down, X-ray background in the detectors goes down....

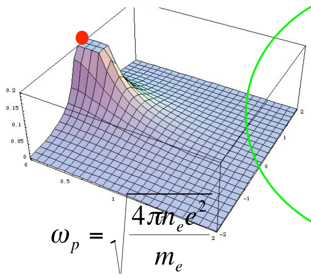
Coherent electron cooling

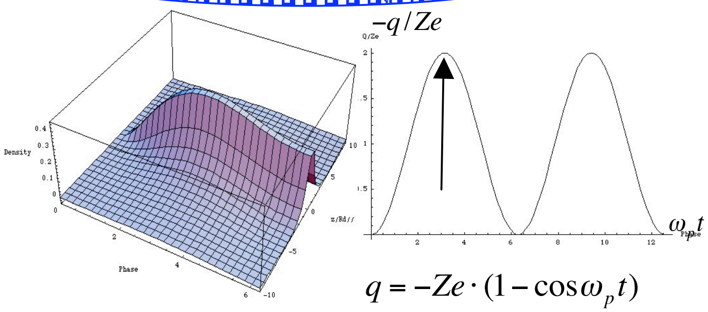


$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} > R_{D//}$$

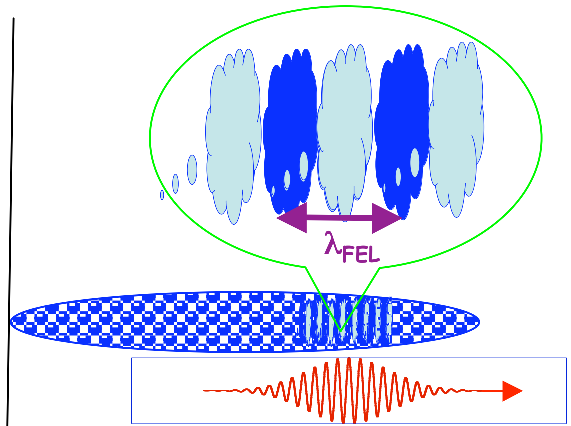
$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_{pe}} << \lambda_{FEL}$$





$$q = -Ze\cdot(1-\cos\omega_p t)$$

$$\varphi_1 = \omega_p L_1 / c\gamma$$



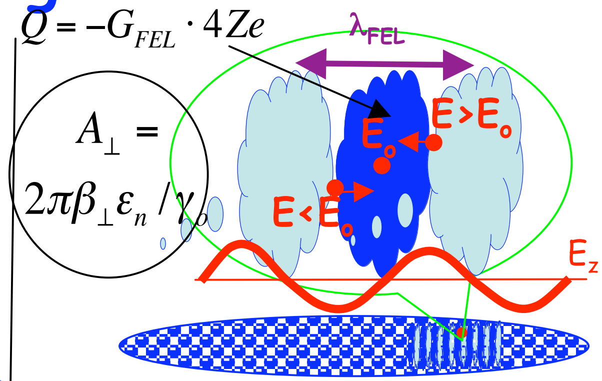
$$\lambda_{FEL} = \frac{\lambda_w}{2\gamma^2}(1+a_w^2) \qquad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$

$$L_G = L_{Go}(1+\Lambda) \qquad \Delta\varphi = \frac{L_{FEL}}{\sqrt{3}L_G}$$

$$G_{FEL} = e^{L_{FEL}/L_G}$$

$$Q = -G_{FEL}\cdot 4Ze$$

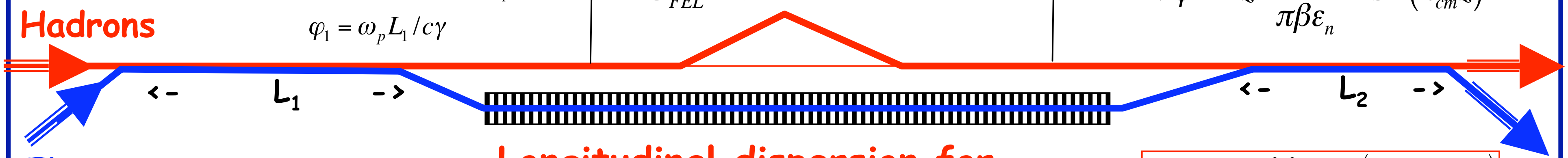
$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$



$$k_{cm} = \frac{\pi}{\gamma_o\lambda_{FEL}} \qquad \boxed{\rho_{amp} = \frac{G\cdot Ze}{2\pi\beta\varepsilon_n}\cdot\frac{4k_{cm}}{\pi}\cos(k_{cm}z)}$$

$$\Delta\varphi = 4\pi\rho \Rightarrow \varphi = -\frac{8G\cdot Ze}{\pi\beta\varepsilon_n k_{cm}}\cdot\cos(k_{cm}z)$$

$$\vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\frac{8G\cdot Ze}{\pi\beta\varepsilon_n}\cdot\sin(k_{cm}z)$$



$$Q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

$$Q_{\lambda_{FEL}}(\max) \approx -2Ze;\ \rho_k = -Ze\frac{4k}{\pi A_\perp}$$

Modulator: region 1

a quarter to a half of plasma oscillation

Longitudinal dispersion for hadrons

$$\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D = D_{free} + D_{chicane};$$

$$D_{free} = \frac{L}{\gamma^2};\ D_{chicane} = l_{chicane}\cdot\theta^2$$

Amplifier of the e-beam modulation via FEL with gain G_{FEL} ~10^2-10^3

$$\boxed{\Delta E_i = -\frac{8G\cdot Z^2e^2}{\pi\beta\varepsilon_n}L_2\cdot\sin\left(k_{FEL}D\frac{E-E_o}{E_o}\right)\cdot\left(\frac{\sin\varphi_2}{\varphi_{p2}}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2}$$

Kicker: region 2

Less than a quarter of plasma oscillation

Was presented in previous talk

Transition to a stationary state:

Coherent Electron Cooling vs. IBS

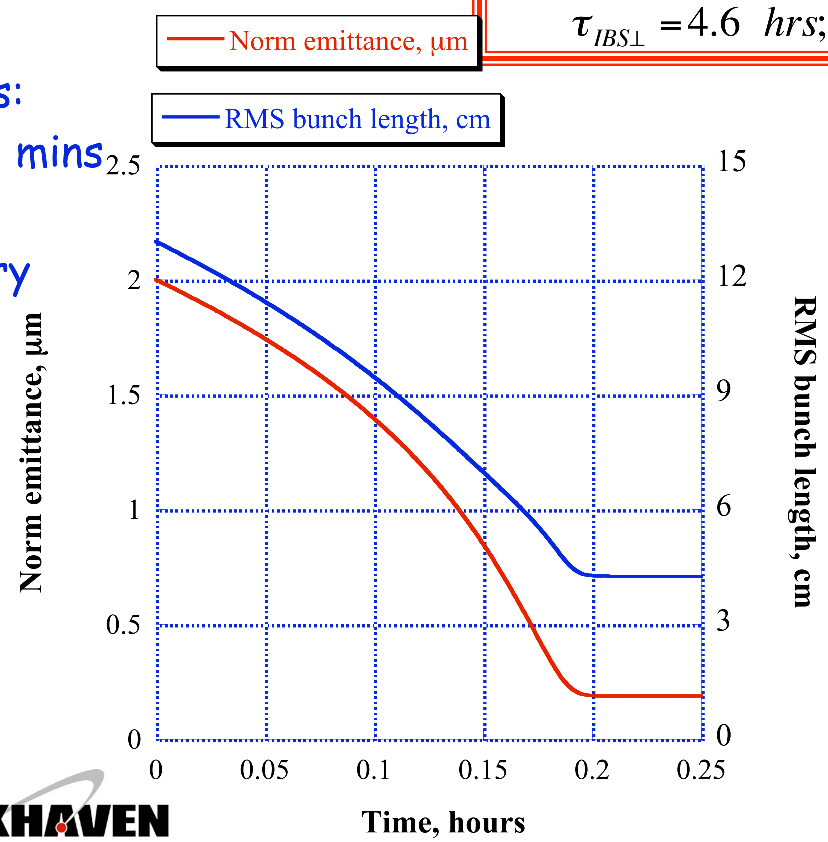
$$X=\frac{\varepsilon_x}{\varepsilon_{xo}};\ S=\left(\frac{\sigma_s}{\sigma_{so}}\right)^2=\left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$
$$\frac{dX}{dt}=\frac{1}{\tau_{IBS\perp}}\frac{1}{X^{3/2}S^{1/2}}-\frac{\xi_\perp}{\tau_{CeC}}\frac{1}{S};$$
$$\frac{dS}{dt}=\frac{1}{\tau_{IBS//}}\frac{1}{X^{3/2}Y}-\frac{1-2\xi_\perp}{\tau_{CeC}}\frac{1}{X};$$

$$X=\frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}}\frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}};\quad S=\frac{\tau_{CeC}}{\tau_{IBS//}}\cdot\sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}}\cdot\sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$

$$\varepsilon_{xn0}=2\,\mu m;\ \sigma_{s0}=13\ cm;\ \sigma_{\delta 0}=4\cdot 10^{-4}$$
$$\tau_{IBS\perp}=4.6\ \ hrs;\ \tau_{IBS//}=1.6\ \ hrs;$$

IBS in RHIC for eRHIC, 250 GeV, $N_p=2\cdot 10^{11}$ Beta-cool, ©A.Fedotov

Dynamics: Takes 12 mins to reach stationary point

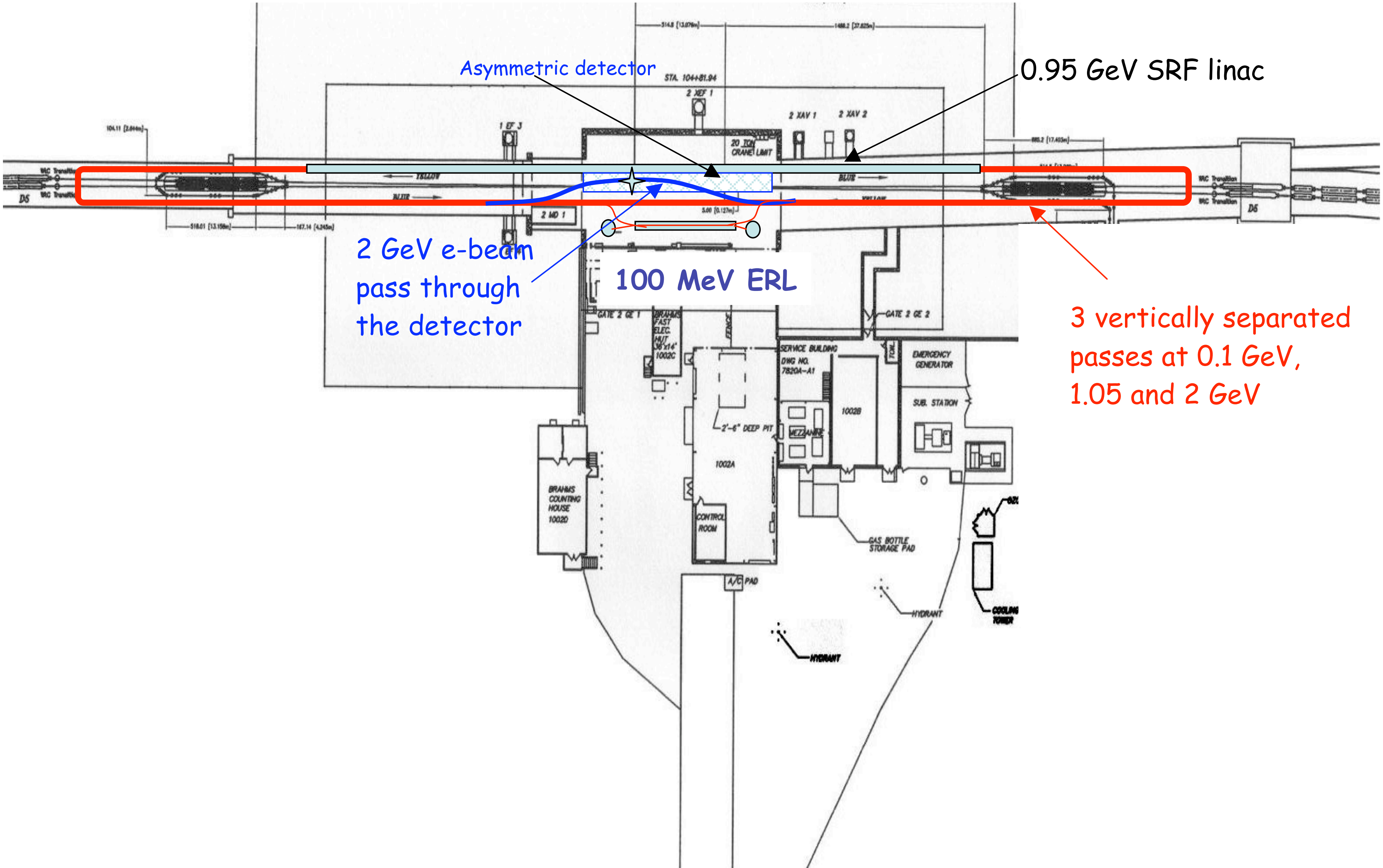


$$\varepsilon_{xn}=0.2\,\mu m;\ \sigma_s=4.9\ \ \mathrm{cm}$$

This allows

a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing β^* from 25 cm down to 5 cm

MEIC with 2 GeV ERL @ IP2



Main R&D Items

- **Electron beam R&D**
  - Energy recovery technology for high power beams (BNL)
    - R&D ERL - high current, low emittance beams, stability, low losses
    - Multi-cavity cryo-module development
  - High intensity polarized electron source (MIT & BNL)
    - Development of large cathode DC guns
      existing current densities ~ 50 mA/cm^2, good cathode lifetime.
    - Development of SRF polarized gun
  - Development of compact recirculating loop magnets (LDRD @ BNL)
    - Design, build and test a prototype of dipole and quadrupole
    - Design, build and test a prototype vacuum chamber
- **Main R&D items for hadron beams (BNL)**
  - Polarized ^{3}He production (EBIS) and acceleration
  - 166 bunches (50% more bunches in RHIC)
  - Proof-of-Principle of the Coherent Electron Cooling

Current vision of eRHIC: Energy Reach and Luminosity

- **MEIC**: Medium Energy Electron-Ion Collider
  - Located at IP2 (with a modest detector)
  - 2 GeV e^- x 250 GeV p (45 GeV c.m.), L ~ 10^{32} cm^{-2} sec^{-1}
- **eRHIC - Full energy, nominal luminosity ,** inside RHIC tunnel
  - 30% increase of RHIC energy is possible with replacing DX magnets
  - Polarized 20 GeV e^- x 325 GeV p (160 GeV c.m), L ~ $4 \cdot 10^{33}$ cm^{-2} sec^{-1}
  - 30 GeV e x 130 GeV/n Au (120 GeV c.m.), L ~ 10^{31} cm^{-2} sec^{-1}
  - 20 GeV e x 120 GeV/n Au (120 GeV c.m.), L ~ $5 \cdot 10^{31}$ cm^{-2} sec^{-1}
- **eRHIC - High luminosity at reduced energy,** inside RHIC tunnel
  - Polarized 10 GeV e^- x 325 GeV p, L ~ 10^{35} cm^{-2} sec^{-1}
  - Smaller improvements (3-4 fold) in e-Ion collisions
  - Polarized positrons (with lower luminosity)

Current vision of eRHIC :
Cost, Re-use, Beams and Energetics

- **MEIC**: Medium Energy Electron-Ion Collider
  - **Cost estimate - $150M** (in 2007 $, Detector is not included!)
  - 90% of ERL hardware will be use in the phase I (and will reduce cost of eRHIC)
  - Energy is limited by fitting the ERL into the existing IP inside RHIC tunnel
  - Possible use of the detector components for eRHIC detectors
  - 50 mA polarized gun is needed for 10^{32} cm^{-2} sec^{-1} luminosity
- **eRHIC - phase I**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 25 mA
  - 20 GeV, 25 mA electron beam losses 1.92 MW total for synchrotron radiation.
  - 30 GeV, 5 mA electron beam loses 1.98 MW for synchrotron radiation
  - Power density is 1 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC - phase II (*if justified by Physics program*)**
  - **Requires crab cavities, new injections, Cu-coating of RHIC vacuum chambers, new level of intensities in RHIC**
  - **Polarized electron source current of 400 mA @** 10 GeV losses are 1.96 MW for synchrotron radiation, power density is 1 kW/meter
  - Polarized positrons (a ring, a Compton source)

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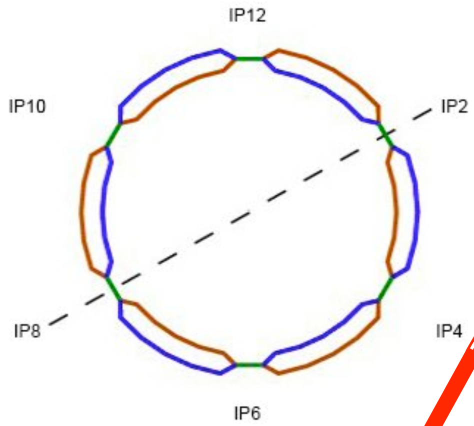
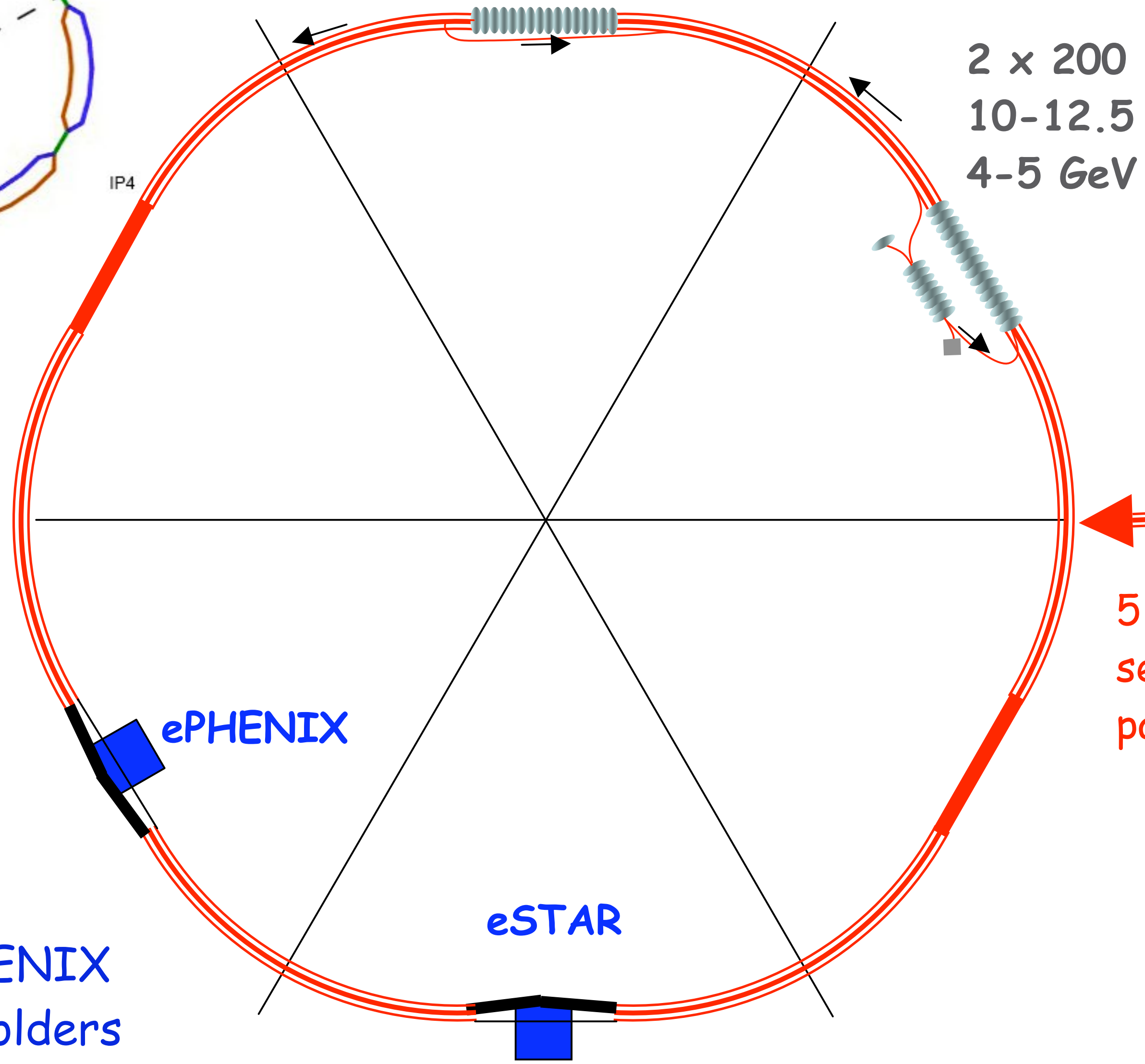
RHIC

20 GeV e x 325 GeV p eRHIC

with ERL inside RHIC tunnel





2 x 200 m SRF linac
10-12.5 MeV/m
4-5 GeV per pass

5 (6) vertically separated passes

eSTAR and ePHENIX are only place-holders

For 10 GeV eRHIC 12 o'clock also can be used for eRHIC detector

Staging of eRHIC with ERL inside RHIC tunnel

RHIC

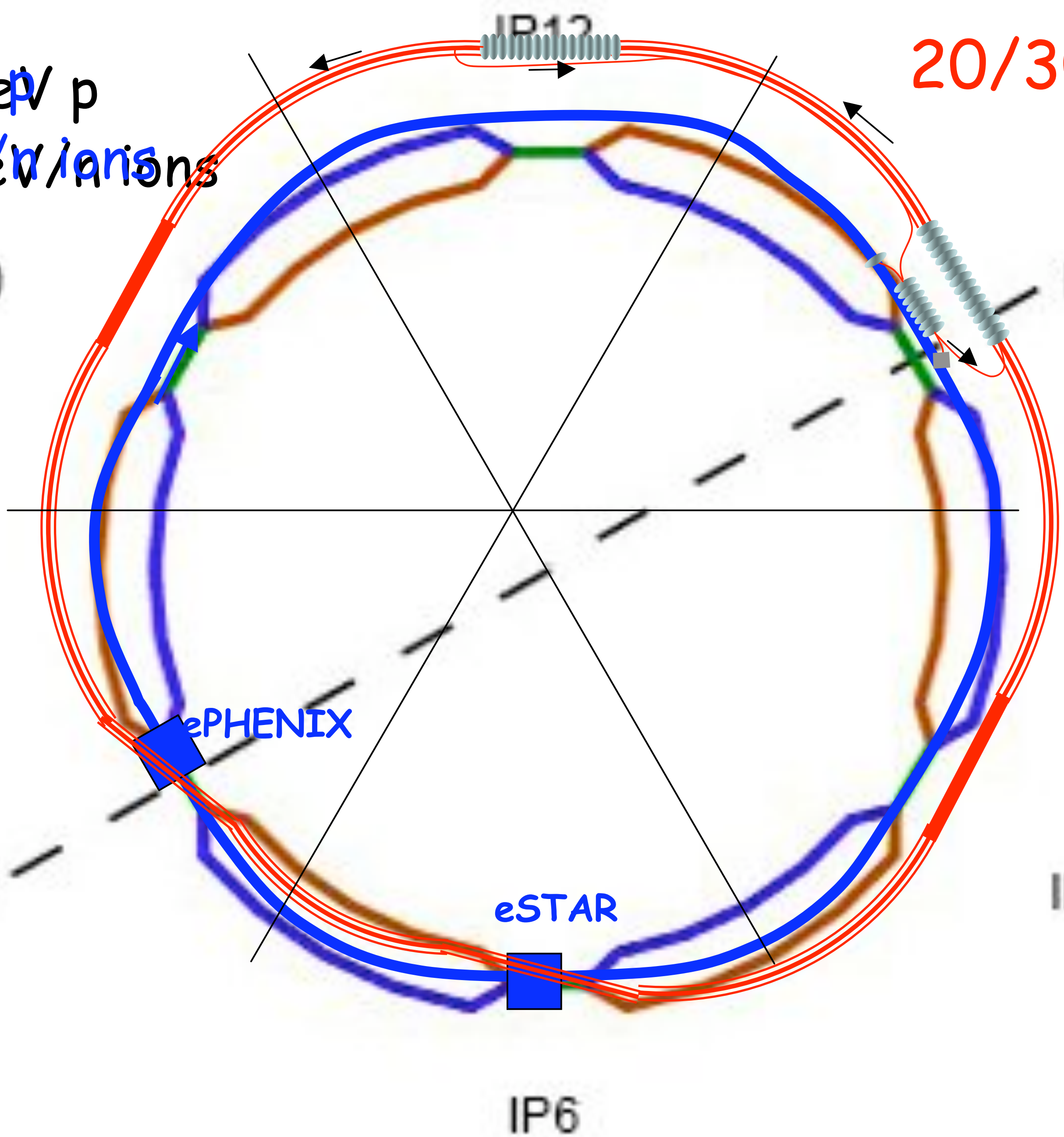
325 GeV p

250 GeV p

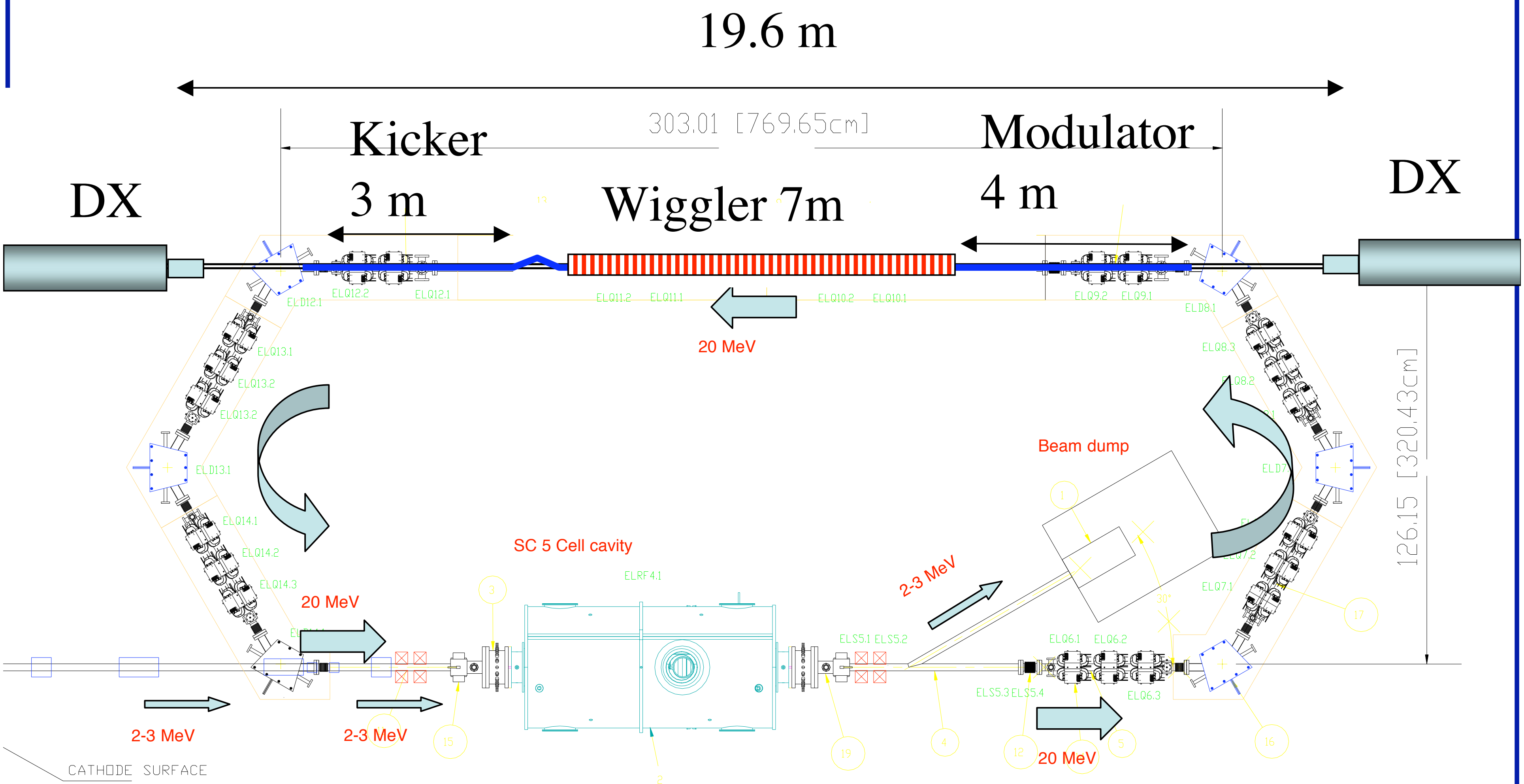
130 GeV/n ions

100 GeV/n ions

20/30 GeV e



IR-2 layout for Coherent Electron Cooling proof-of-principle experiment



Conclusions

- High energy, high luminosity ERL-based electron-ion and polarized electron-proton collider is the most promising approach for eRHIC
- Presently there is no show-stoppers and a significant amount of R&D
- There is a clear possibility for eRHIC staging
- Coherent-electron cooling is the key for eRHIC's performance
- Proof-of-principle of coherent electron cooling is one of high priorities of eRHIC R&D